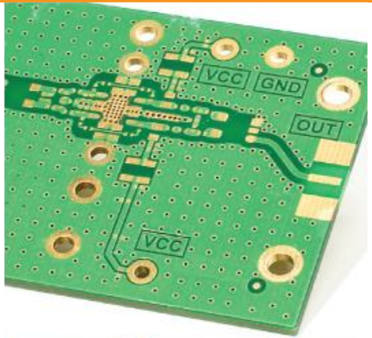

Beamforming and Total System Efficiency Optimization of Poorly Isolated Antenna Arrays

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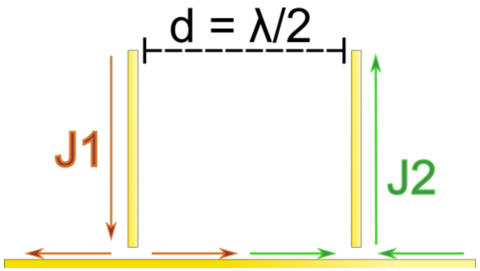
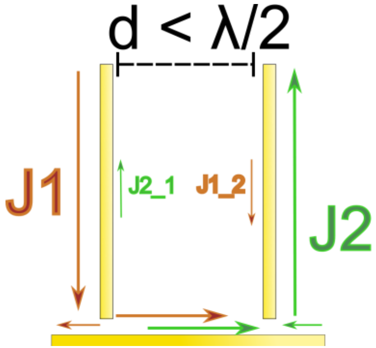
Contents

Antenna Arrays

- An array is an antenna comprised of a number of radiating elements whose inputs are combined (IEEE definition)
- If the current distributions of the elements only vary by a constant phase and amplitude, the resulting radiation pattern can be analytically calculated as a product of the *individual element pattern* and *array factor*
- However, modern designs often have limited spatial freedom, leading to decreased inter-element isolation or finite ground plane effects

➢ Results obtained using the array factor are no longer valid





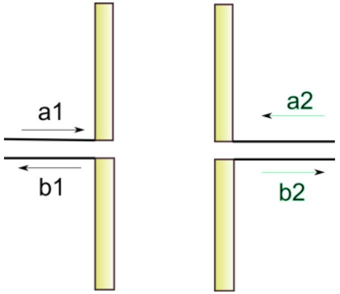
Total System Efficiency vs. System Efficiency

- There is a major difference between total efficiency and total system efficiency
  - Total efficiency is calculated for each port when a single port is excited at a time and the other ports are terminated by their matching circuits
  - Total system efficiency is calculated for a given **excitation vector** as the ratio of radiated power from the array and the sum of available powers from the ports
- As the power couples from one port to another upon the simultaneous excitation, the classical definition of reflection and transmission coefficients no longer properly describe the impedance of the port

➢ *Active reflection coefficients* (ARCs) are needed

Active Reflection Coefficients

- If both ports of a 2 port system are excited simultaneously, the wave traveling backwards at port one can be expressed as
$$\boldsymbol{b_1 = S_{11}a_1 + S_{12}a_2}$$
- The *active reflection coefficient* of port one is defined as
$$\boldsymbol{ARC_1 = \frac{b_1}{a_1} = \frac{S_{11}a_1 + S_{12}a_2}{a_1}}$$
  - Part of the *forward traveling wave* of port 2 becomes part of the *backward traveling wave* in port 1 and vice versa!
- If the mutual coupling term $\boldsymbol{S_{12}}$ is very small, the equation for active reflection coefficient reduces to that of S_{11}
$$\boldsymbol{ARC_1 \approx \frac{S_{11}a_1}{a_1} = S_{11}}$$

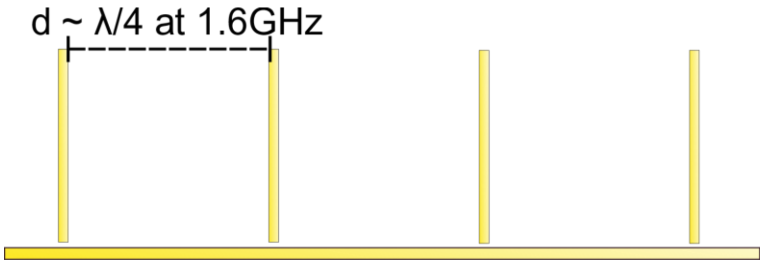


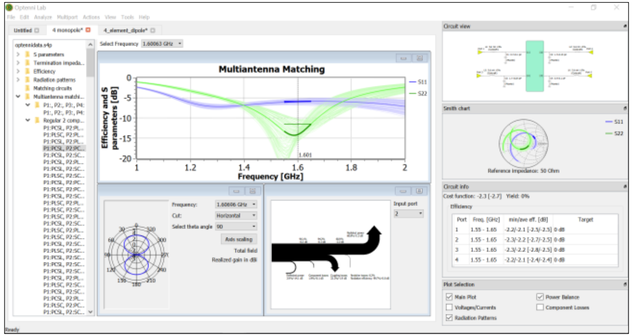
Loss Mechanisms in an Array

- The power which is not radiated has to either:
  - Dissipate as heat in the radiating element due to non perfect *radiation efficiency*
  - Couple to other ports as *coupling losses*
  - Dissipate as heat in the matching circuitry and feeding network as *component losses*
  - Reflect back as *reflection losses*
- To improve the **total efficiency of a system**, one must optimize all of these simultaneously

Example Array – 4 Element Monopole Array

- We study an array comprised of 4 monopoles over a finite ground plane,
- Elements are at about 1/4th of a wavelength from another at 1.6 GHz
- The analysis is carried out in ***Optenni Lab***, a software platform for antenna system optimization
  – The design input data, S-parameters and radiation patterns, can be measured or transferred from a full-wave EM simulation software



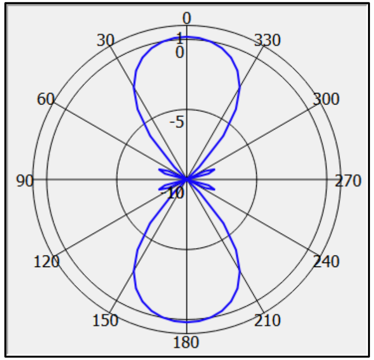


Example Problem: 4 Element Monopole Array

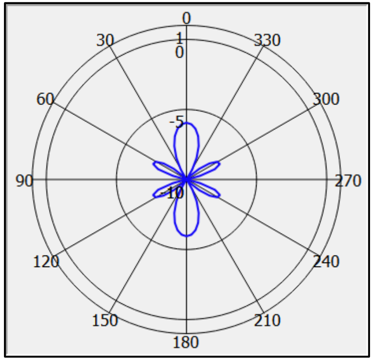
- Due to the presence of the other elements as well as the finite ground plane, the edge and center elements have significantly different matching levels and resonance frequencies
- As the frequency gets smaller, the electrical distance between the elements decreases, resulting in more and more deformed radiation pattern

Fixed feed vector: $1\angle 0°$, $1\angle 180°$, $1\angle 0°$, $1\angle 180°$

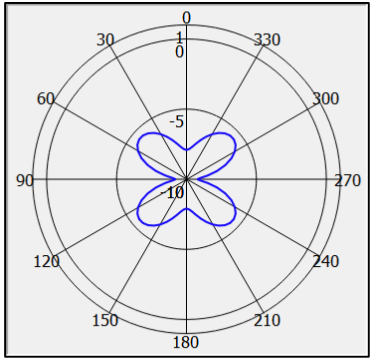
3 GHz



2.4 GHz



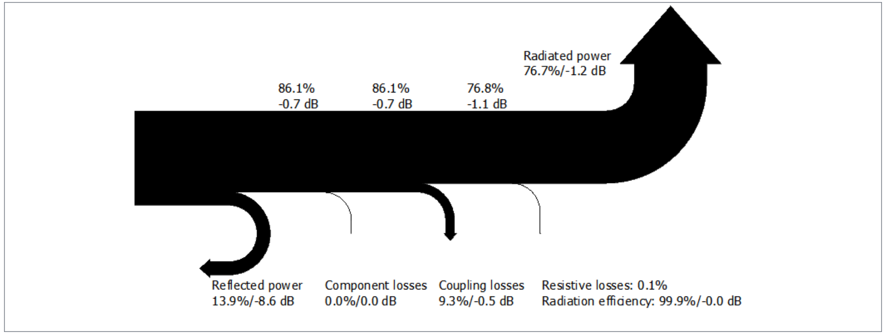
1.4 GHz



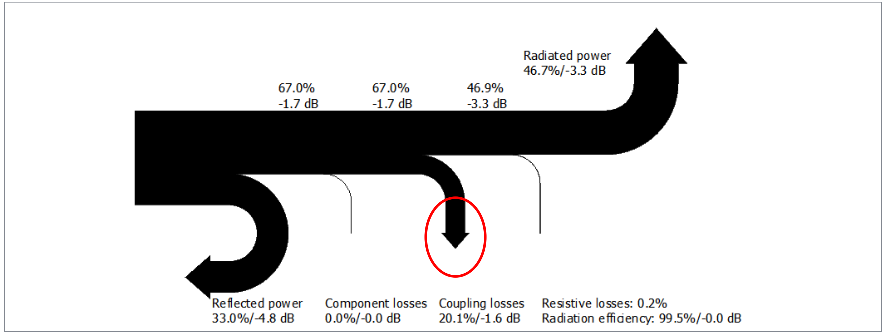
Initial Operation

- We are designing a system for the 1.55 to 1.65 GHz band
- Deducing efficiency information from the multiport S-parameters is difficult
- Let's look at the **power balance** instead at 1.6 GHz
  - The edge elements are quite well matched, but the center elements are detuned due to their interaction with the nearby elements

Edge elements at 1.6 GHz



Center elements at 1.6 GHz

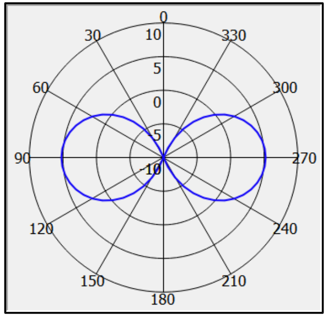


Steering the Beam of a Coupled Array

- For a coupled arrays, the ARCs are functions of the feed vectors
- The array radiation pattern does not behave as expected by the array factor. Especially the end-fire excitation (middle) results in a nearly non-radiating mode
- However, an end-fire pattern can be retained by manually modifying the feed vectors

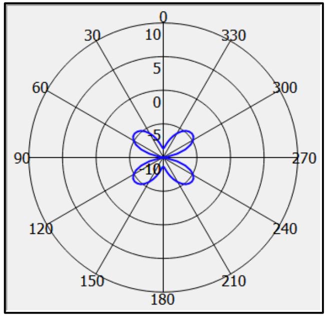
Broadside

$1\angle 0°, 1\angle 0°, 1\angle 0°, 1\angle 0°$



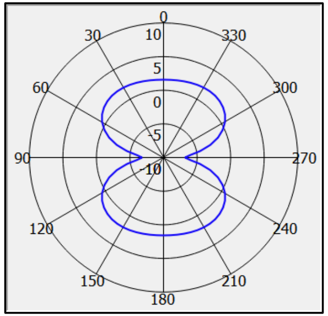
Analytical endfire

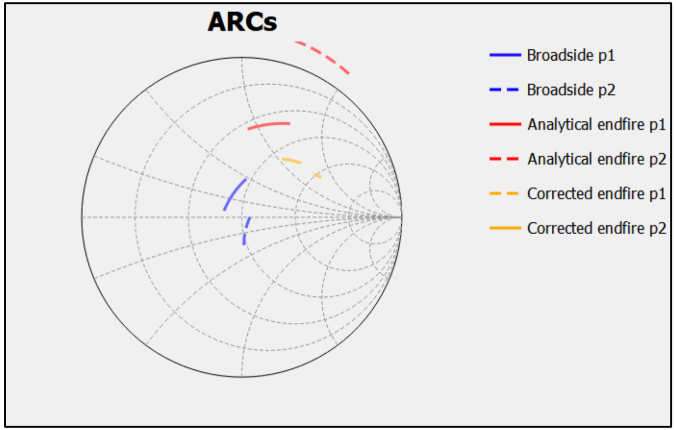
$1\angle 0°, 1\angle 180°, 1\angle 0°, 1\angle 180°$



Corrected endfire

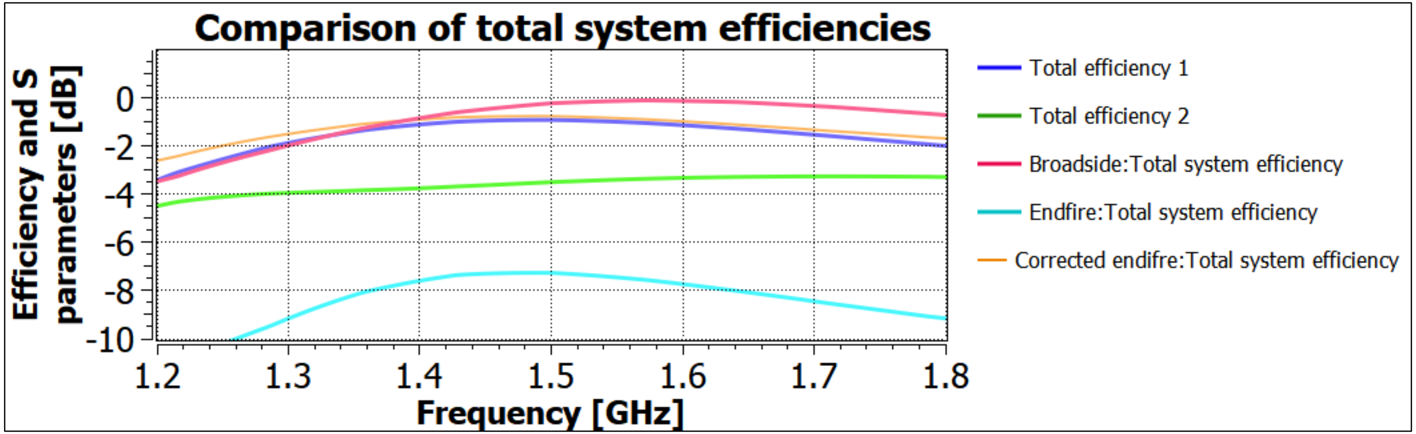
$1\angle 0°, 1\angle 0°, 1\angle 180°, 1\angle 180°$





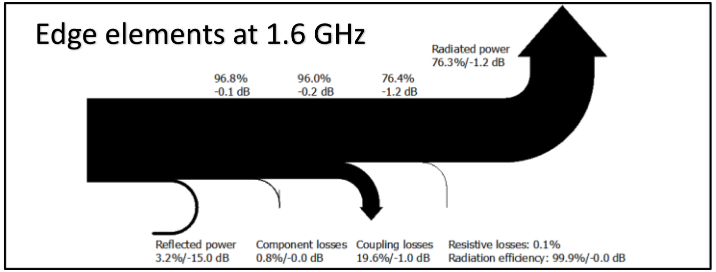
Total System Efficiency of the Coupled Array

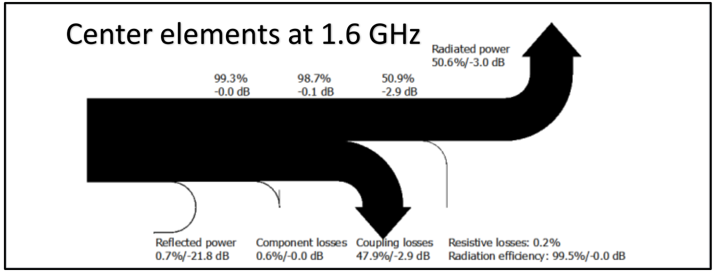
- As the ARCs for the beams fluctuate, so do the total system efficiencies:
  - Broadside beam has a higher total system efficiency than any individual element efficiency
  - Analytical endfire beam has ~5dB worse efficiency than the worst element
  - Corrected endfire beam's efficiency is on par with the element efficiencies

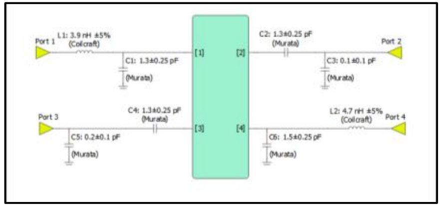


Optimizing Impedance Matching with a Matching Circuit

- We let Optenni Lab first to synthesize a matching circuit using Coilcraft DC0402 and Murata GJM15 components that minimize **only the reflection losses** for each port with 2 components per port
  - The matching losses decreased, but the coupling losses have increased
    - The net change in system performance is close to 0 dB
  - The significantly increased coupling will make the total system efficiency more sensitive to different feed vectors



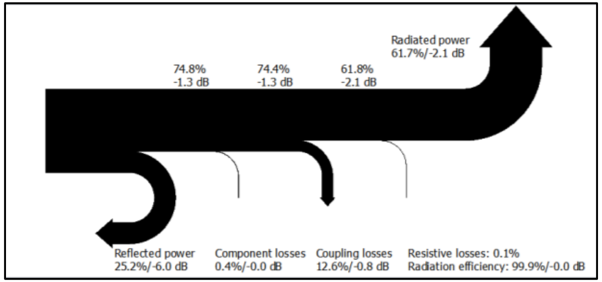




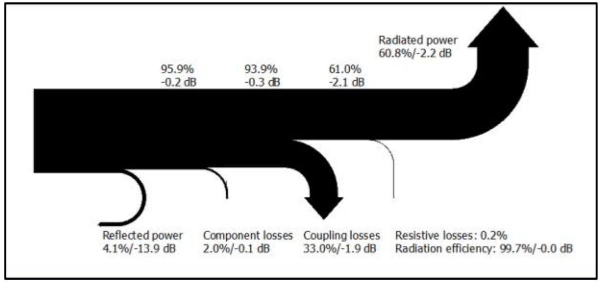
Optimizing Total Efficiency with a Matching Circuit

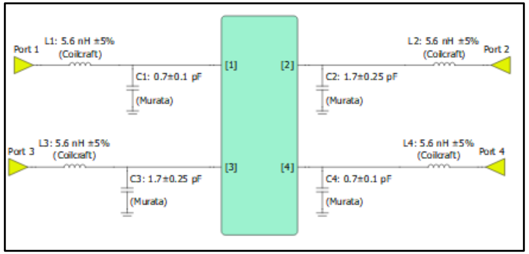
- We use the same components, but change the optimization **target to best total efficiency** in Optenni Lab
  - This is a reasonable optimization target for especially MIMO arrays, where the feed vectors cannot be determined beforehand
- It seems that the efficiency of port 1 has actually decreased, but the system minimum performance, dictated by the centre elements, has increased ~1dB

Edge elements at 1.6 GHz



Center elements at 1.6 GHz



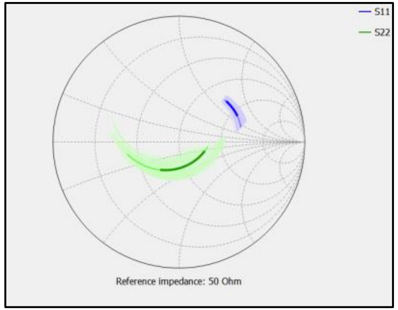


Tolerance Sensitivity of the Matched Solution

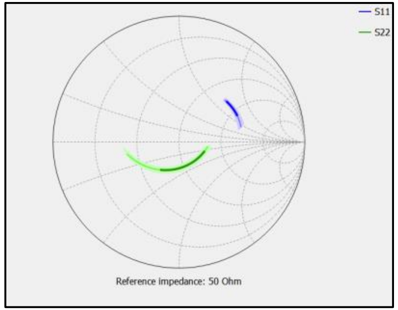
- Optenni Lab can automatically search for the most tolerance insensitive solution, which will lead to a robust ARC operation as well
- There is a 2-component topology which has equally robust operation with loose component tolerances than the previous topology had with tight ones

➢ Topology 2 is more economical and we'll continue with it

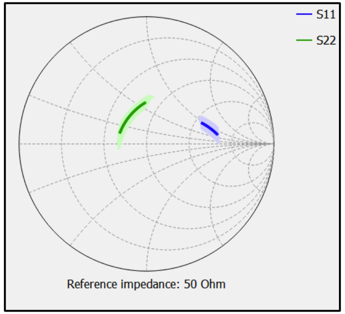
Topology 1: Loose tolerance variants



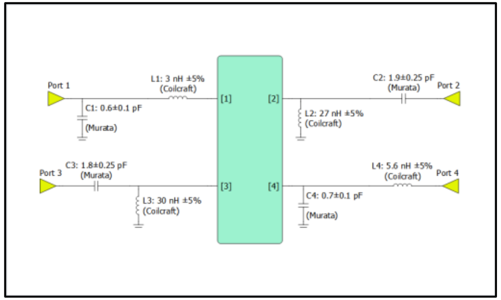
Topology 1: Tight tolerance variants



Topology 2: Loose tolerance variants



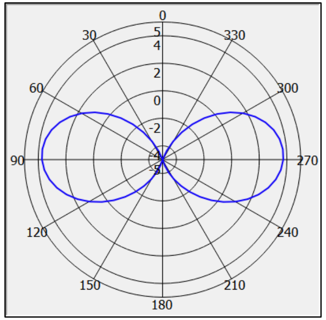
Topology 2



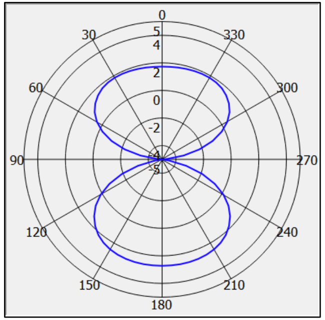
Steering the Beam of the Matched Array

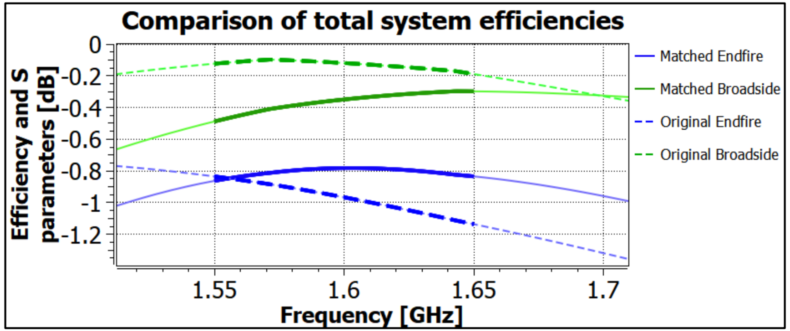
- As the matching circuit changes the amplitude and phase at the antenna inputs as well as the inter-element coupling, the feed vectors have to be readjusted
- The matched solution has higher total system efficiency, and it is also much less dependent upon the beam direction

$1\angle 0°, 1\angle -20°, 1\angle -10°, 1\angle 0°$



$1\angle 0°, 1\angle 0°, 1\angle 170°, 1\angle 220°$





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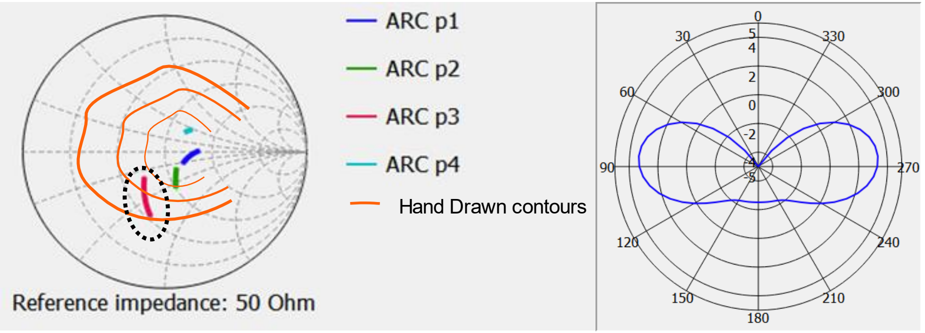
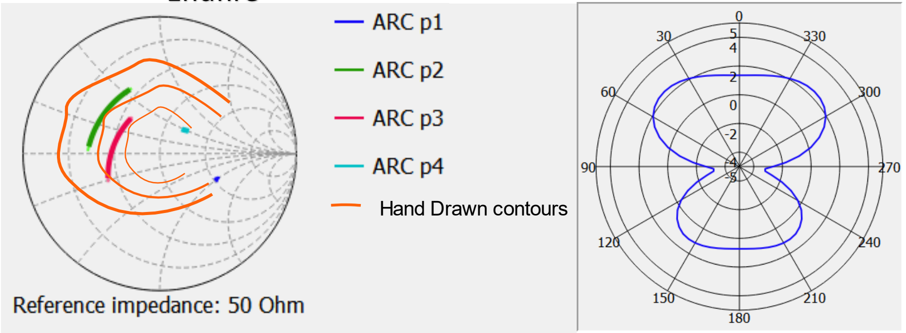
Effect of ARC on PA Load-Pull

- One can manually study the impact of the ARC load-pulling of the power amplifiers by overlaying the load-pull contours and the ARCs of the respective beams
- In the mock-up scenario illustrated below, e.g. the port 3 PA for broadside excitation would require amplitude adjustment because ARC for port 3 crosses the load-pull contour lines, while other ports' ARC do not cross any contour

Broadside



Endfire



Conclusions

- Optenni Lab allows for quick optimization and assessment of array performance where computationally heavy full-wave EM simulations are only used to create the initial data
- Arrays consisting of elements with poor isolation can be used, but analytical tools won't yield accurate results when designing or analysing them
  - The realizable radiation directions and intensities might be lower than for an array with good inter-element isolation
- Matching circuits can be implemented to improve the performance of an antenna array, by:
  - Decreasing the variation of ARC and hence increasing total system efficiency
  - Manipulating the ARC to a wanted load region for the PA
  - Re-tuning antenna elements to the desired frequency bands

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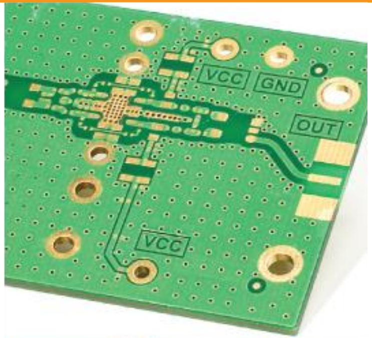

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